useful reactions

K_0 regeneration

decay to $(2\pi$ violates $CP)$

$K_L \rightarrow 3\pi \quad (CP=-1)$

$K_S \rightarrow 2\pi \quad (CP=+1)$

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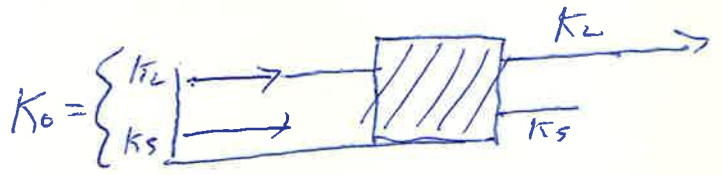
$CP(K_0) = -\overline{K_0}$
$CP(\overline{K_0}) = -K_0$

$K_L = \frac{1}{\sqrt{2}}(K_0 + \overline{K_0})$
$K_S = \frac{1}{\sqrt{2}}(K_0 - \overline{K_0})$

$\overline{K}^0 + p = \Lambda^0 + \pi^+$



produced in $\pi^- + p = \Lambda^0 + K_0$.

$\overline{K_0}$ produced in $\pi^+ + p = K^+ + \overline{K_0} + p$.

neutrino reactions ① $\overline{\nu}_e + p = n + e^+$ (Reines & Cowan) (reverse $n \rightarrow p + e^- + \overline{\nu}_e$)

② $\nu_\mu + n = \mu^- + p$ (Lederman discovery)

but not $\nu_\mu + n = e^- + p$.

③ $\nu_\mu + n = \nu_\mu +$ hadrons (neutral currents)

$K_0 \rightarrow \mu^+ + \mu^-$ forbidden.

cf Weinberg (1967) - Salam (1968) unification e.m. & weak. (2 W's charged & neutral, & massive vacuum) cf $e^+ + p = e^+ + p$ and $n \rightarrow p + e^- + \overline{\nu}$

Resonances $\pi + N \rightarrow N^* \rightarrow \pi + N$ (Fermi - reaction for 1st large resonance)

$\pi + N \rightarrow \rho + N \rightarrow \pi + \pi + N$ (ρ-meson discovery)

antiproton $p + p \rightarrow p + p + p + \overline{p}$

Associated production (Pais 1952)

$\pi^+ + n \rightarrow \Lambda^0 + K^+$

Λ^0 decay $\Lambda^0 \rightarrow ~~p + \pi~~ \;\; p + \pi^- \}$

$S \quad -1 \qquad 0 \quad 0 \qquad\qquad 0 \quad 0 \qquad -1 \quad +1 \quad S$

pion decay $\pi \xrightarrow{\text{strong}} N + \overline{N} \xrightarrow{\text{weak}} \mu + \nu$

P.T.O.

weak-interaction coupling

axial vector coupling constant

$$H = G\left[\left(\bar{\psi}_p \gamma_\mu \left(C_V + \gamma_5 C_A\right)\psi_n\right)\left(\bar{\psi}_e \gamma_\mu (1+\gamma_5)\psi_\nu\right)\right.$$

$$J = J_A + J_V$$

$$H' = \int \underset{\sim}{J}(x) \cdot \underset{\sim}{J}^{+}(x)\, d^3(x)$$

In general $J = J_L + J_B$ $\left\{ \begin{array}{ll} J \cdot J \to J_L^2 & \text{leptonic} \\ J_L \cdot J_B & \text{semi-leptonic} \\ J_B^2 & \text{non-leptonic} \end{array} \right.$

$$C_A = +1.25\, C_V$$

Experiment confirmed by theory.

renormalized axial vector coupling constant

w-particle

w-particle lower bound on mass → 4.4 GeV, May 73

Tachyon

Tachyon proposed 1962 by Bilaniuk, Deshpande & Sudarshan.
named by ~~E~~ Feinberg in 1967 $\left\{ \begin{array}{l} \text{Tardons} < c \\ \text{Luxons} = c \\ \text{Tachyons} > c \end{array} \right.$

$$\text{Mass} = i\, m_0$$

$$E = \frac{m_0 c^2}{\sqrt{v^2/c^2 - 1}}.$$

Discovery of Ω^-

$$K^- + p \to \Omega^- + K^+ + K^0$$

$\Omega^- \to \Xi^0 + \pi^-$

$\Xi^0 \to \Lambda^0 + \pi^0$

$\Lambda^0 \to \pi^- + p$

$\pi^0 \to \gamma + \gamma$

$\gamma \to e^+ + e^-$, $\gamma \to e^+ + e^-$

12 oct 73

beam energies

28 gev	CERN	1960	
7 gev.	Rutherford	1963 (Nimrod)	
33 gev	Brookhaven	1960	
70 gev	Serpukhov	1967	
200–500 gev.	N.A.L. Batavia, Illinois	(1972) → 400 gev	
300 gev.	cern.		

Storage rings

25 gev p.p.	CERN	1971
0.55 e^+e^-	Orsay	1967
0.5 e^+e^-	Stanford	1966
0.7 e^+e^-	Novosibirsk	1966

(Berkeley) → Bevatron 1954, 6.2 gev it requires 6 gev beam to produce an anti proton
experiment carried out in 1955 by Chamberlain, Segré, Wiegand & Ypsilantis

Cosmotron 1953 1.4 gev (Brookhaven)

<u>Useful numerical results</u>

1 Fermi $= 10^{-13}$ cm 1 mb $= 10^{-27}$ cm^2

radius hydrogen atom $= e^2/mc^2 \cdot \alpha^{-2} \simeq \hbar^2/e^2 m = 0.5\times10^{-8}$ cm

Compton wavelength $= e^2/mc^2 \cdot \alpha^{-1} \simeq \hbar/mc \simeq 0.4\times10^{-10}$ cm

radius of electron $= e^2/mc^2 \simeq 0.3\times10^{-12}$ cm

range for pion is 1.4 Fermi

10^{-13} cm $\equiv$ 200 MeV particle

10^{-23} sec $\equiv$ 65 MeV resonance width

$(\text{GeV})^{-2} \equiv 0.4$ mb

Experimentally range nuclear forces is $\sim 2\times10^{-13}$ cm $\equiv$ 100 MeV mass

($1-2 \times10^{-13}$ cm $\equiv$ 100–200 MeV particle)

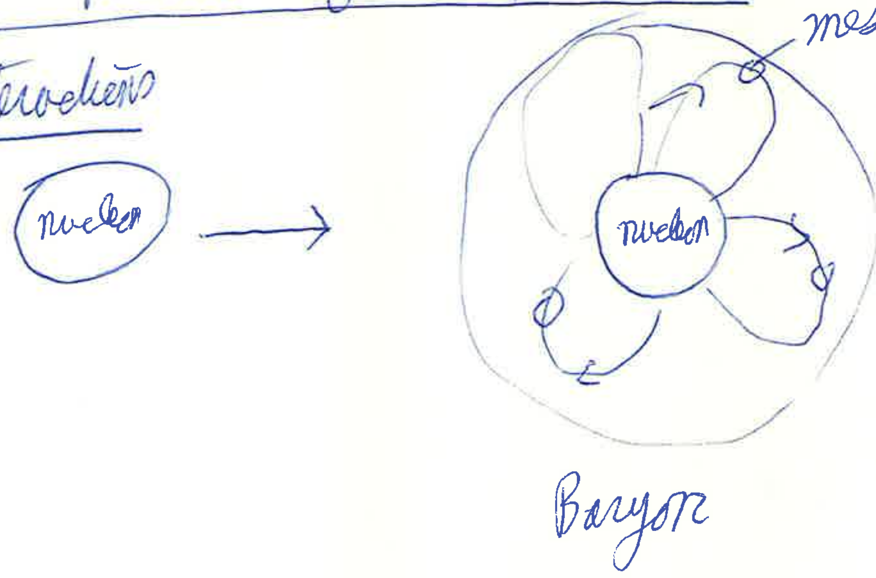
<u>C.m energies</u> $E^{Total}_{c.m.} = \sqrt{2 E_{lab}}$ in GeV.

In colliding beams $E^{Total} = 2E_{lab}$

30 GeV beam → 8 GeV available
200 " " → 20 GeV available
for production.

Simple picture of the particles

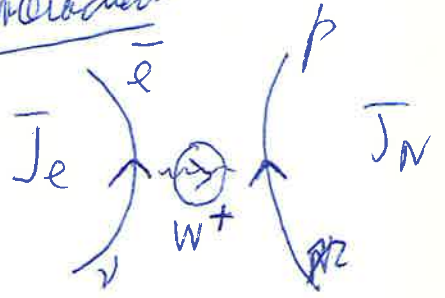
Strong Interactions



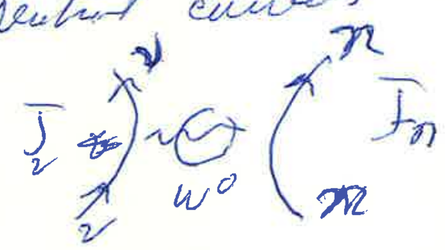
(pions for $N^*(1236)$ etc.
kaons for Λ^0 etc.

cf. old
strong-coupling
theory of
meson-fields
Pauli 1946
(Meson Theory of Nuclear Forces.
but note problem
of strangeness
Λ^0 involves K meson.

weak interactions



or neutral currents

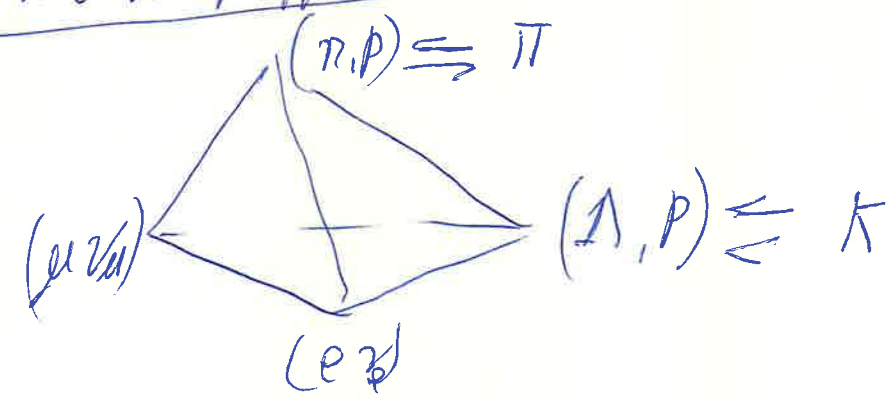


e.m. Interactions

or in terms of currents

p.T.O

Gell-Mann Puppi tetrahedron



then $\Lambda_0 \xrightarrow{\text{weak}} \cancel{p+}\ N + \underbrace{N + \bar{N}}_{\xrightarrow{\text{strong}}\ \pi}$

$K \xrightarrow{\text{strong}} \Lambda\, p \xrightarrow{\text{weak}} N\, N \xrightarrow{\text{strong}} \pi + \pi +$

$\Lambda \rightarrow N + K$ not energetically possible

<u>Associated production</u>

$\pi^+ + n = \Lambda^0 + K^+$

Interpretation of coupling constant (cf. Fermi) (14)

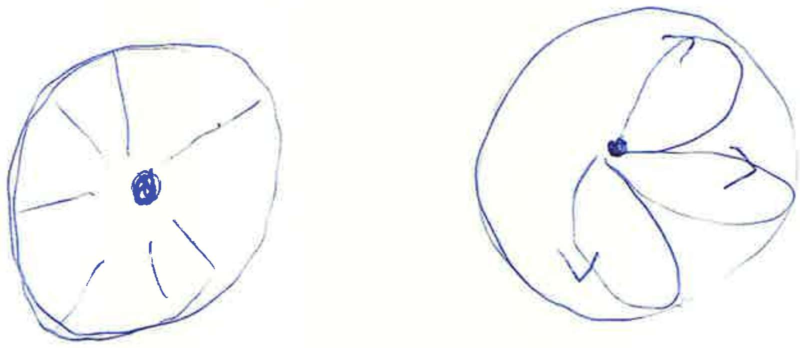
Interaction parameter such as $e^2/\hbar c$

measures. mean $n^{\underline{o}}$ of particles of type II

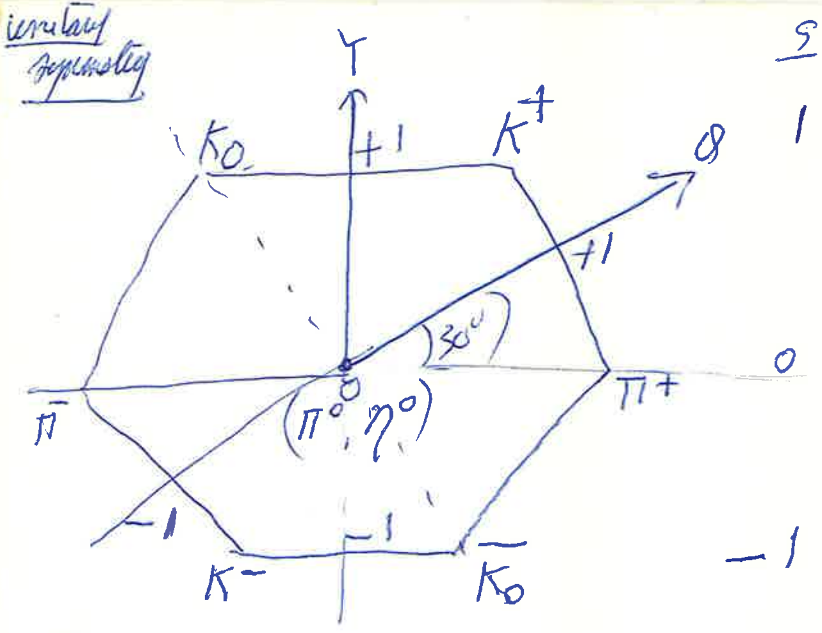
surrounding particle of type I.

For $\psi = \psi_{I} + \sum_{n} \psi_{I + n II} \cdots$

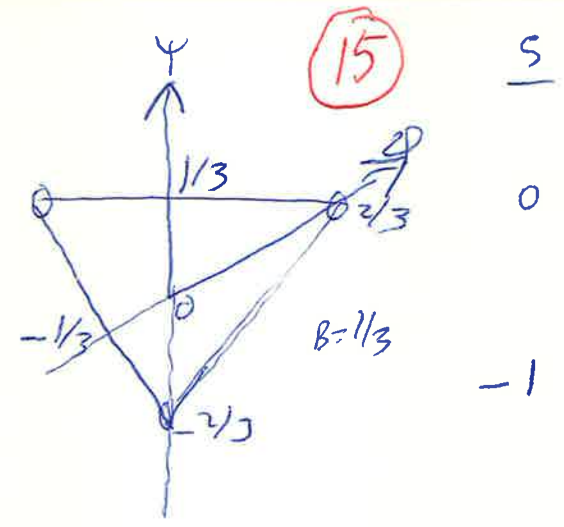
$$\bar{n} \sim e^2/\hbar c$$



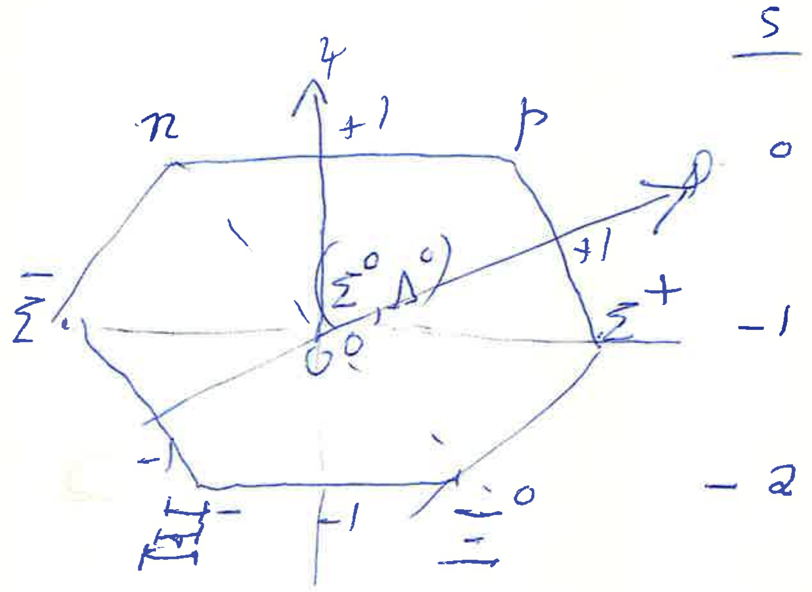
unitary symmetry



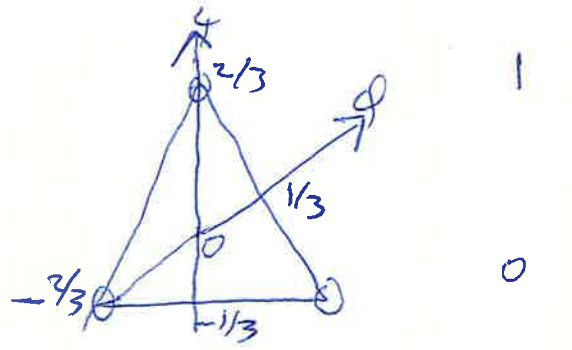
mesons



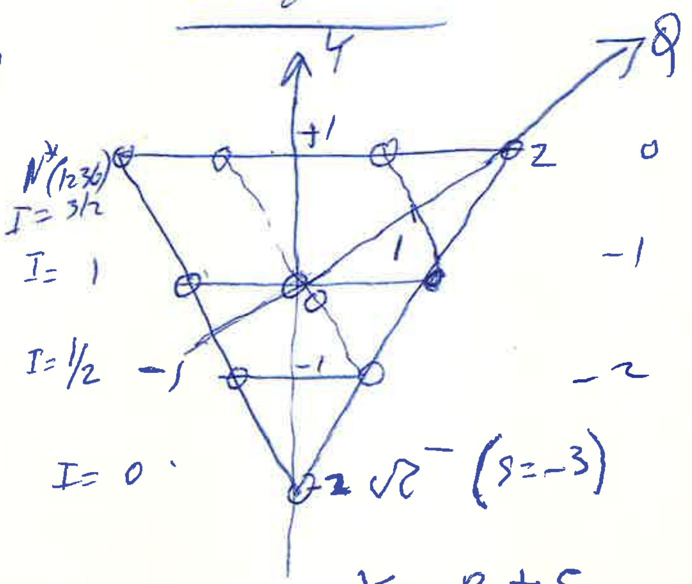
quark



baryons



antiquark



mesons $3 \times 3^* = 8 \oplus 1$

baryons $3 \times 3 \times 3 = 10 \oplus 8 \oplus 8 \oplus 1$

$Y = B + S$

$Q = \frac{1}{2}Y + T_3$

Range - energy relation

$\Delta E = mc^2$

$\Delta t = \hbar / mc^2$

distance travelled $< c\Delta t = \hbar / mc$

maximum range is $\hbar / mc$.

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Photon

~~classical~~ wave (Maxwell) $\xrightarrow[\text{field quantization}]{}$ Quantized wave

particle (photons) N

$\Downarrow$ N particles (quantized)

↓

Heisenberg, Pauli 1929

{ Quantized particle (electrons) N $\underset{\text{2nd quantization}}{\Longrightarrow}$ Electron quantized wave }

(matter field ≡ 1 particle S. Eqn.)

Jordan, Klein

Jordan, Wigner

↓

Fock 1932.

Equivalence Sets of oscillators
↔ set of particles

ter Dirac 1927

Jordan, ~~Pauli~~ Klein ~~1928~~ 1927

↳ fermions Jordan, Wigner 1928

~~N classical particles $\xrightarrow{\text{1st quantization}}$ N quantized particles Schrödinger Eqn $\underset{\text{Equiv.}}{\overset{\text{2nd quantization}}{\Longrightarrow}}$ quantized field (set of quantum oscillators)~~

(1927) Dirac (photons) ?

(1927) Jordan, Klein (Bosons N.R.)

(1928) Jordan, Wigner (Fermions N.R.)

classical field $\xrightarrow{\text{field quantization}}$ quantized field (set of q. oscillators) $\Longrightarrow$ N particle Schr. Eqn

(1928) Jordan, Pauli

(1929, 1930) Heisenberg, Pauli

[(1934) Pauli, Weisskopf (charged scalar field)]

Scattering of localized beam

$\theta \sim me/p$

$\Delta\theta \sim \lambda/D = \frac{\hbar}{pD} \Rightarrow \frac{me}{p} = \theta.$

But $D \ll \hbar/me$

forward peak $\sim \frac{1}{q^2+m^2} = \frac{1}{p^2 \sin^2 \frac{1}{2}\theta + m^2}$

peak w/ $\Delta\theta$ seen $\sim$

$p\Delta\theta \sim m \quad \Delta\theta \sim m/p$

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the paraquark

$$d\sigma \sim \left| \int e^{-ik'\cdot r}\, V(r)\, e^{ik\cdot r}\, dr \right|^2$$

$$\sim \quad V^2(q) = \rho^2(q)\frac{1}{q^4} \Big/ q \text{ is momentum transfer}$$

$$q = 2k \sin\tfrac{1}{2}\theta.$$

now $\nabla^2 V \propto \rho$

$$V(r) = \int V(q)\, e^{iq\cdot r}\, dr$$

$$\nabla^2 V = \int \underbrace{q^2 V(q)}_{\rho(q)}\, e^{iqr}\, dr . = \rho(r)$$

$$\left(\text{so } V(q) = \rho(q)\cdot\frac{1}{q^2}\right)$$

~~$\rho(q)$~~ now $\rho(r) = \int \rho(q)\, e^{iqr}\, dq$

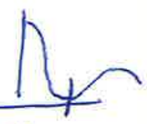
if $\rho(0) = 0$

(by antisymmetry $\psi(r_1 - r_2) = -\psi(r_2 - r_1)$.

so $\psi(0) = -\psi(0) = 0$.)

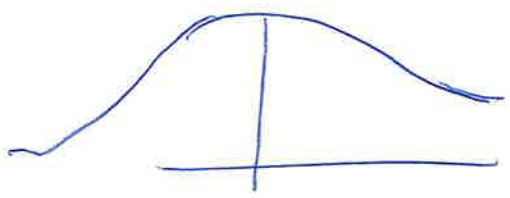
then $\int \rho(q) \, dq = 0$

so $\rho(q)$ has a zero. $\rho^2(q)$ either



not observed experimentally

(like $\dfrac{1}{1+q^2/k^2}$)



N.B. x-section $\propto$

Chew, Gell-Mann & Rosenfeld   Sci Am. 210 (2): 74
popular article.   (1964)

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Sum Rule

$\langle \psi | (AB - BA) | \psi \rangle = \langle \psi | C | \psi \rangle$

$= \sum_n \left(\langle \psi | A | \phi_n \rangle \langle \phi_n | B | \psi \rangle \right) - \sum_n \left(\qquad \right)$

$= \langle \psi | C | \psi \rangle.$

↳ $\sum_n \left(\phi_n | A | \psi \right)^2$

↳ Sum of transition strengths to ϕ from all n states.

plot

Heisenberg's Unified Field Theory

Universal length arises since 3 constants are needed to establish a system of units e.g. c, $\hbar$ & ℓ

then $m = \dfrac{\hbar}{\ell c}$ gives scale of masses

"Eq. of motion for matter is a quantized non-linear wave equation for a wave field of operators that simply represents matter, not any specified kind of waves or particles." This wave equation will lead to integral equations with eigensolutions representing the particles. They are the mathematical forms replacing the regular solids of the Pythagoreans.

Eqs:—

$$i\sigma^{\nu}\frac{\partial \chi}{\partial x^{\nu}} + \ell^{2}\sigma^{\nu}\chi\left(\chi^{*}\sigma_{\nu}\chi\right) = 0.$$

χ is a 2-component spinor. , proposed 1959

described in book 1960